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Effects of Unexpected Lateral Mass Placement on Trunk Loading in Lifting

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Study Design. A repeated measurements experiment of spinal loading in healthy subjects.

Objectives. To test whether unexpected lateral mass placement increases low back loading and trunk movement when subjects are lifting a mass in upright posture.

Summary of Background Data. Epidemiologic studies suggest that sudden, unexpected loading will lead to low back pain. Also, asymmetric loading is considered to be harmful to the spine. It can be anticipated that unexpected asymmetric loading will increase the risk of injury even more.

Methods. Ten subjects lifted in an upright posture a crate, in which a mass of 10 kg was placed laterally at the left side either expectedly or unexpectedly. The crate reaction forces, body movements, and trunk muscle activity were measured. From these, the L5-S1 net moments and muscle forces were estimated.

Results. Unexpected lateral placement of the mass caused no clear increase in peak low back loading. The stiffness of the trunk was lower in the unexpected condition, which, in combination with inadequate net moments produced, resulted in movement of the trunk to the side of the displaced mass.

Conclusions. Unexpected lateral mass placement does not increase the compression force. Perturbed trunk movement and lower muscle forces indicated a decreased stability of the spine, which may imply an injury risk. [Key words: lifting, low back, load, asymmetric, sudden loading, stability] **Spine 2003;28:764–770**

Low back pain (LBP) is common in the general population. More than 70% of the population in industrialized countries will experience LBP at least once during life.[1] In most cases, the origins of LBP remain obscure.[2] However, epidemiologic studies have reported an association between lifting and LBP.[1,3,4] In addition, sudden, unexpected loading on the low back appears to be related to LBP.[5,6] It would therefore seem likely that the combination of these risk factors, unexpected loading during lifting, may impose a serious health risk.

The relationship between sudden loading in lifting and mechanical back load as an indicator of the risk of LBP has been studied previously.[7,8] In these experiments, subjects were lifting a box, of which the mass was unexpectedly increased. As subjects anticipate the mass they are going to lift,[9] the unexpected increase in mass may lead to sudden loading. However, in the studies cited, the unexpectedly high object mass did not cause an increase in low back loading. Thus, no support for inferences regarding causality of the association between sudden loading and LBP during whole body lifting was found. However, these studies were restricted to symmetric perturbations. Sideward perturbations during lifting may occur commonly in occupational manual material handling; for example, consider a refuse collector lifting two refuse bags of different weight, one in each hand, or a warehouse- clerk lifting a box in which the mass is unequally distributed.

When subjects expect the center of mass to be lateral to the midsagittal plane, they perform anticipatory postural adjustments by activating contralateral muscles before exerting force on the object.[10] On occasions when the position of the mass is placed laterally without the subjects expecting this, subjects are anticipating a symmetric mass distribution and will not produce a lateral bending moment. Consequently, the trunk will be pulled laterally by the mass lifted. Lifting objects in combination with trunk lateral bending and twisting increases the injury risk.[1,3,4] In addition, this perturbation may lead to a corrective response involving high muscle forces, which could be damaging to the spine.[11] Consequently, sudden asymmetric loading may cause an increased risk of low back injury.

The aim of this study was to investigate whether unexpected lateral mass placement in lifting increases the loading of the spine compared with expected lateral mass placement. Subjects lifted a crate, in which a mass was displaced to the left either expectedly or unexpectedly. All lifts were performed at a self-selected lifting velocity. Body movements, trunk muscle activity, and crate reaction forces were recorded. Low back loading was studied by analyzing three-dimensional (3-D) net moments, summed muscle forces, trunk lateral movement, and compression forces at the L5-S1 joint.

Materials and Methods

In this experiment, 10 men participated (age, 22.1 ± 2.6 years; height, 1.83 ± 0.06 m; body mass, 73.8 ± 4.1 kg), none of whom had a history of back pain. All subjects gave written consent before the experiment. The local ethics committee had approved the procedures. The subjects were asked to lift a crate

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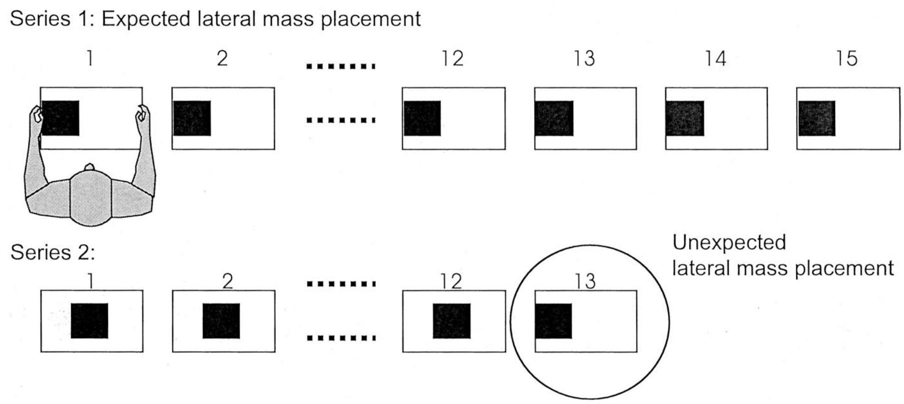

Figure 1. Experimental protocol.

of 2.6 kg, in which a mass of 10 kg was placed laterally at the left side. The crate was placed 0.2 m in front of the subjects' toes at a 0.71-m high table. The subjects were asked to lift the crate symmetrically until the flexion of the arms was 90°. They were asked to keep their trunk upright, so that the lifting movement was restricted to the arms. The subjects either knew the location of the mass (expected condition), or it had been laterally displaced without the subjects' knowledge (unexpected condition).

To be able to compare the lifting of the unexpected and expected lateral mass placement, the experiment consisted of two lifting series (Figure 1). In the first series, subjects lifted 15 times a crate in which the mass was placed 0.125 m left of the center of the crate. This was called the expected condition. In the other lifting series, subjects were forewarned that the mass could have been replaced before they lifted the crate. At the start of this lifting series, subjects lifted the crate, in which the 10-kg mass was placed centrally. After 12 lifting movements, the mass was shifted to the left by 0.125 m, without the subjects noticing. This last lifting movement was the unexpected condition. Between the lifting movements, subjects were asked to wear nontransparent glasses, so it was possible to move the mass in the crate without the subjects noticing. After each lifting movement, the mass was lifted out of the crate to ensure that the auditory cues were not different between trials.

The net moment at the lumbosacral (L5-S1) joint was calculated as a function of the relevant external forces and accelerations described by Hof.[12] Anthropometric data (body mass, length of segments, standing height) were measured to estimate segment anthropometry.[13] The resultant net moment was calculated as the square root of the squared net moment components. A positive flexion-extension moment represents an extension moment. During the lifting movement, kinematic data were recorded at 100 Hz using an automated video-based recording system (Optotrak™, Northern Digital Inc., Canada). Fourteen light emitting diodes (LEDs) were placed bilaterally at the upper part of the body to indicate the location of the following joints: the hip joint, the lumbosacral joint (as in de Looze, *et al.*[14]), the spinous process of the first thoracic vertebra, the lateral border of the acromion, the elbow joint (epicondylus lateralis), and the wrist joint (ulnar styloid). One LED was placed at the back of the hand to indicate the position of the center of the hand. The location of the crate center of mass was calculated with the help of three LEDs at both sides of the crate. The lateral bending angle was calculated as the projection of the trunk markers in the frontal plane. A positive lateral bending angle indicates a movement to the right. To focus on the effects of the perturbation with respect to the initial posture, the angle at the start of the lifting movement was defined as zero. The starting angle before correction was not significantly different between both conditions (analysis of variance [ANOVA], $P = 0.94$). Simultaneously with the movement registration, the reaction force on the crate was measured with a force-platform placed below the crate (Kistler 9218B). All analogue force signals were amplified, sampled (100 Hz), filtered (10 Hz, fourth-order Butterworth filter), and stored.

Electromyographic (EMG) data were obtained from bilateral surface recordings of the prime back and abdominal muscles. Before the experiment, disposable EMG electrodes (Ag/AgCl) were attached after cleaning and abrasion of the skin. The center-to-center electrode distance was 2.5 cm. The electrodes were placed on the following muscles: the erector spinae muscles at the level of L1 and T9, the latissimus dorsi, and the external and internal oblique muscles. The oblique muscles were subdivided into a lateral and an anterior part.[15] The electrodes of the lateral part of the internal obliques were placed at the lumbar triangle, whereas the electrodes of the anterior part were placed cranial to the inguinal ligament. The lateral part of the external obliques was recorded midway between the iliac crest and the rib cage in the midaxillary line, whereas the anterior part was recorded at the umbilical level and above the anterior iliac spine. The electrodes were positioned 3 cm lateral to the midspine at L1 and T9 to measure the erector spinae muscle, and 6 cm lateral to the midspine at T9 to measure the latissimus dorsi muscle. The EMG signals were amplified 20 times (Porti-17, Twente Medical Systems, The Netherlands), band-pass filtered (10–400 Hz), and stored on disc at a sample frequency of 1,600 Hz with a 22-bit resolution. The EMG signals were high-pass filtered (digital finite impulse response filter, 30 Hz) to reduce the influence of possible movement artifacts and electrocardiographic signals,[16] band-stop filtered between 49 and 51 Hz to reduce artifacts from the electric mains, rectified, and low-pass filtered (second-order Butterworth filter, 2.5 Hz).[17] All digital filtering was bidirectional to avoid phase shifts of the signals. For normalization of the signals, subjects performed seven tests of maximum voluntary isometric contractions, as described by McGill.[18] All tests were repeated three times. The maximum value per muscle of all 21 measurements was used for normalization.

To estimate muscle forces and spinal compression, an EMG-driven model was used, as described in van Dieën *et al*[19] and van Dieën and Kingma,[20] comprising 90 muscle slips crossing the L5-S1 joint. Muscle forces were estimated as the product of the maximum muscle stress, normalized EMG am-

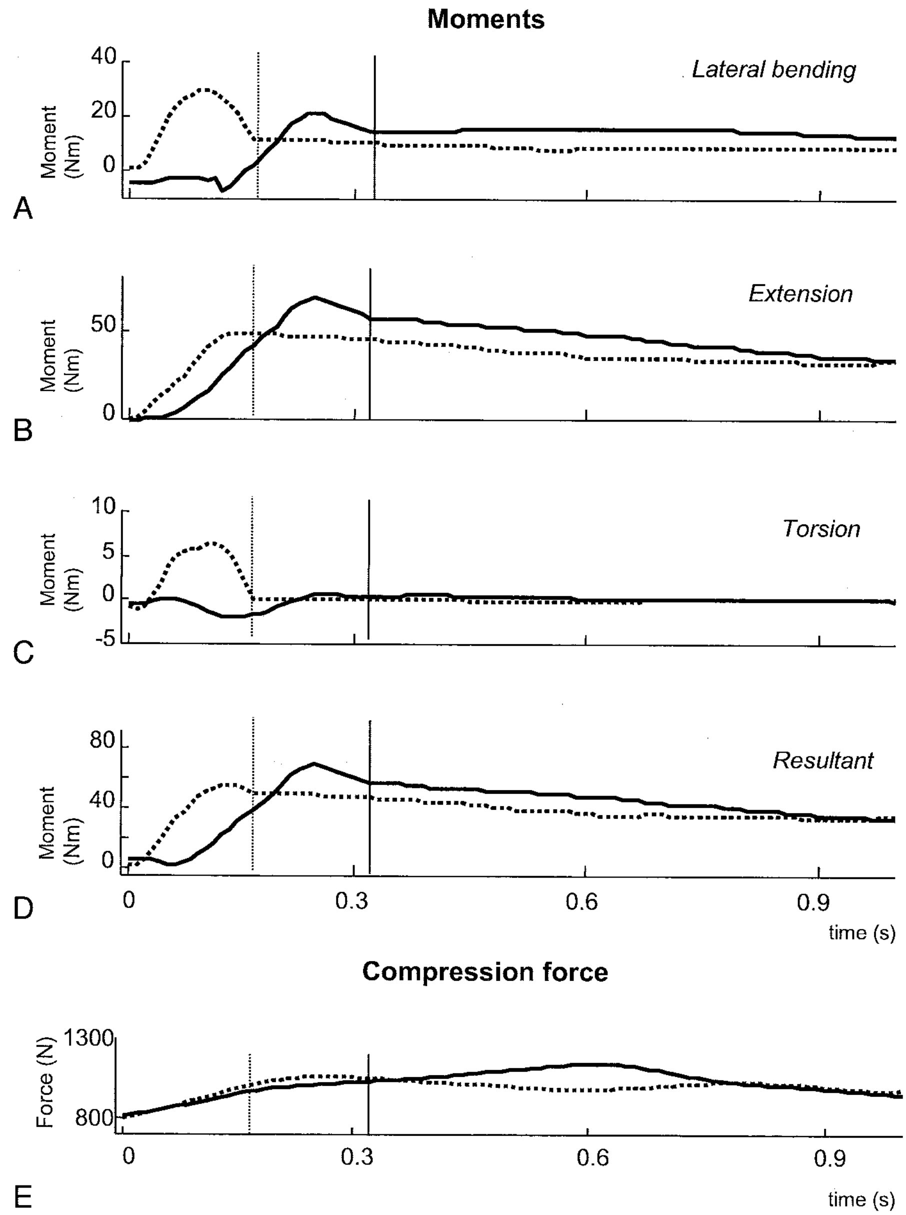

Figure 2. Typical example of times series of the lateral bending moment (**A**), extension moment (**B**), torsion moment (**C**), resultant moment (**D**), and compression force (**E**). Time zero is the onset of force exerted on the crate. The solid curve represents the unexpected condition, and the dashed curve represents the expected condition. The vertical lines indicate the instant the crate was fully lifted off the platform. The dashed line represents the lift-off in the expected condition, and the solid line represents the lift-off in the unexpected condition. Although in this example peak compression force appeared to be higher in the unexpected compared with the expected condition, this difference was not significantly different among the subjects.

plitude, and correction factors for the instantaneous muscle length and contraction velocity. These correction factors are based on dynamical properties of human and animal muscles, as described by van Zandwijk,[21] and passive length tension properties, as described by Woittiez *et al.*[22] The muscle lengths and contraction velocities were calculated on the basis of 3-D trunk angles. To calculate the electromechanical delay, the resultant muscle moment and the resultant net moment were correlated for all trials of each patient. The phase shift derived from this correlation was used to shift the EMG signal. The calculations of muscle moments and compression force were repeated with the time-shifted EMG, and these results were used. Maximum muscle stress was iteratively adjusted to obtain maximum agreement (least squares) between the time series of the muscle moments and net moments. Summed muscle forces were calculated as the summed scalar values of the muscle forces in all three planes.

The muscles were divided in four groups according to their mechanical function to circumvent the problem of crosstalk in the interpretation of surface EMG results:[10] left and right extensors and flexors. The anterior parts of the external and internal oblique were defined as flexors. The lateral part of the external oblique was also added to the flexors; although the flexor moment arm is negligible, its lateral flexion component is not. The lumbar and thoracic erector spinae muscles, the lateral part of the internal oblique, and the latissimus dorsi muscle were classified as extensor muscles.

The peak values of the lifting movement in the unexpected condition were compared with the average of the peak values of the last three lifting movements in the expected series. A paired *t* test was used to evaluate the effect of expectation on the peak values of the compression force, net moments, lateral trunk angle, and grouped EMG values. In addition, the summed muscle force relative to the resultant net moment was calculated at the instant of peak resultant net moment to obtain an indication of the stiffness of the spine at this instant. To study the timing of the muscle activity, the effect of expectation on the instant of peak summed muscle force relative to the instant of peak resultant net moment was evaluated with a paired *t* test. Results were considered significant at $P < 0.05$.

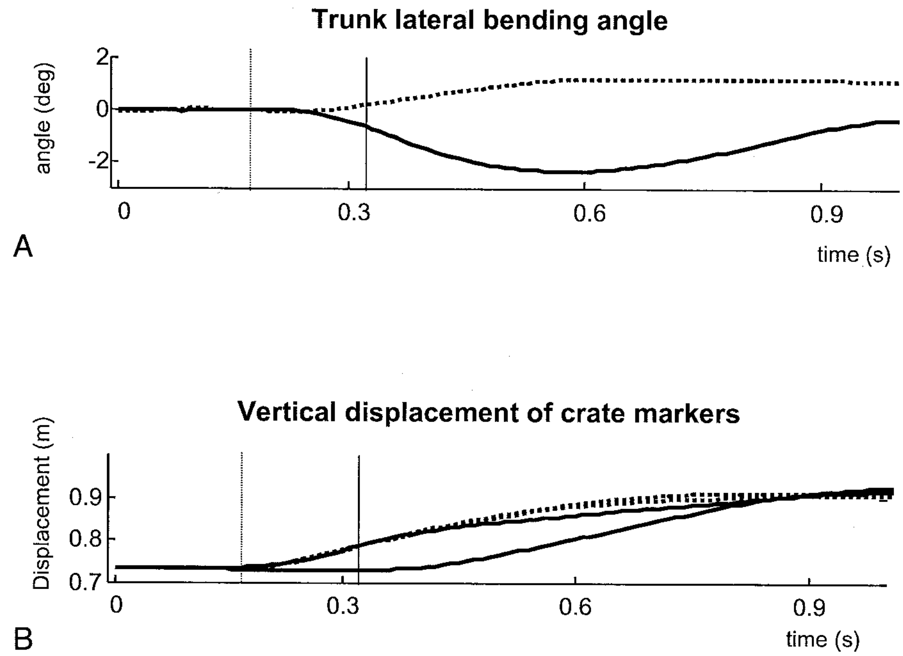

Figure 3. Typical example of times series of the trunk lateral bending angle (**A**) and the vertical displacement of two crate markers (**B**). Time zero is the onset of force exerted on the crate. The solid curve represents the unexpected condition, and the dashed curve represents the expected condition. The vertical lines indicate the instant the crate was fully lifted off the platform.

■ Results

To illustrate the results, an example of one subject lifting a laterally placed mass in the expected and unexpected condition is described. In the expected condition, the subject starts to exert a net lateral bending moment just after the start of the lifting movement (Figure 2), which is defined as the instant the subject first exerts a vertical force on the crate. Before the crate is fully lifted from the platform, the peak in net lateral bending moment, net extension moment, resultant net moment, and net torsion moment is reached. The latter net moment is probably produced to move the crate toward the body. After lift-off, no peaks in net moments are seen, and the crate is moved symmetrically (Figures 2 and 3). In the unexpected condition, the subject starts to exert a net lateral bending moment later than in the expected condition. Before the crate is lifted from the platform, the net lateral bending moment increases, but not to the level seen in the expected condition. The direction of the torsion net moment in the unexpected condition differed from that in the expected condition (Figure 2). Because of the unexpected change in mass distribution, the subject rotates the crate and lifts the right (no mass) side. This asymmetrical crate position is not corrected before the crate has been fully lifted from the platform (Figure 3). Before lift-off, but especially after lift-off, the trunk is pulled to the side of the lateral mass in the unexpected condition, whereas this was not the case in the expected condition (Figure 3). The relatively low lateral bending net moment in the unexpected condition, which was produced relatively late, can explain this lateral movement.

In the unexpected condition, loading of the low back in terms of peak resultant net moment and the net extension moment was significantly increased by approximately 10% compared with that in the expected condition (Table 1). Although the peak resultant net moment

Table 1. Average Values* of Various Study Factors†

	Expected	Unexpected	*P* Value
Peak compression force (N)	1451 (± 242)	1444 (± 194)	0.83
Peak net moment			
Lateral bending (Nm)	23.7 (± 6.9)	17.6 (± 5.1)	0.005
Extension (Nm)	59.3 (± 9.2)	66.6 (± 9.6)	0.01
Torsion (absolute value) (Nm)	5.2 (± 1.5)	5.3 (± 3.9)	0.90
Resultant (Nm)	62.6 (± 7.8)	68.8 (± 9.6)	0.01
Peak lumbar lateral angle	1.5 (± 0.9)	−0.7 (± 2.4)	0.01
Ratio muscle force resultant moment at instant peak resultant moment (m^{-1})	25.0 (± 5.2)	20.0 (± 2.5)	0.03
Timing difference between peak resultant moment and peak summed muscle force (msec)	180 (± 6.5)	330 (± 4.1)	0.08

* Standard deviation in parentheses.
† Included are the the peak compression force, three-dimensional net moments, the net resultant moment and the lumbar lateral angle. The ratio between the summed muscle forces and peak resultant moment at the instant of peak net resultant moment and the timing difference between the occurrence of peak resultant moment and peak summed muscle force are also shown.

Table 2. Average Values* of the Peak Normalized Muscle Activity of the Functional Muscle Groups

Muscle Group	Expected	Unexpected	*P* Value
Left flexors	4.8% (± 3.3%)	5.7% (± 3.6%)	0.95
Left extensors	9.6% (± 4.2%)	10.3% (± 4.2%)	0.734
Right flexors	5.4% (± 3.0%)	5.6% (± 3.3%)	0.746
Right extensors	9.7% (± 2.1%)	10.4% (± 1.2%)	0.172

* Standard deviations in parentheses.

was increased, the relative summed muscle force at the instant of peak resultant net moment was 20% lower than in the expected condition ($P = 0.03$), indicating a lower stiffness of the trunk. Lateral bending of the trunk to the side of the mass was found larger in the unexpected condition, probably caused by this lower stiffness. In contrast, in all lifting movements in the expected condition, the trunk moved to the contralateral side, with a mean peak angle of 1.5° (Table 1).

Although the relative muscle force at the instant of resultant net moment was lower in the unexpected condition, no significant differences were found in the peak grouped muscle activity (Table 2). Also, no significant difference in peak compression force was found in the unexpected condition (Table 1) ($P = 0.83$). Both results point to a difference in timing of peak muscle activity between the two conditions. In the unexpected condition, an almost significantly later occurrence of the peak summed muscle force relative to the occurrence of the peak in resultant net moment was found (Table 1) ($P = 0.008$). No significant differences were observed in the peak absolute net torsion moments between the expected and unexpected condition (Table 1). However, the direction of the net torsion moment was significantly different between both conditions ($P = 0.025$). Because of the low values, this difference is probably not physiologically relevant.

As an indication of the quality of the predictions of the EMG-driven model and of the estimated compression force, the absolute average error between the net extension moments and the estimated extensor muscle moments was calculated. The mean absolute average error was 11.8 ± 7.2 Nm. The absolute error in the lateral flexion moment was 7.9 ± 1.5 Nm, and in torsion moment was 4.0 ± 3.8 Nm. The mean r^2 value, calculated over all moments, was 0.88 ± 0.06. The overall gain value necessary to equal the muscle moments and net moments was 81.7 ± 28.3.

Discussion

This study was designed to investigate the effects of expectation on low back loading when lifting a laterally placed mass. Subjects lifted a crate, of which the mass was either expectedly or unexpectedly placed to the side. The peak resultant net moment and the peak extension net moment were significantly higher than in the expected condition. Spinal loading is usually quantified using shear forces and compression forces. Shear forces are sensitive to anatomic assumptions[23] and were therefore not quantified in this study. Our initial expectation was that cocontraction, which is described in other studies analyzing sudden asymmetric loading,[24,25] would lead to high compression forces in the unexpected condition. It appeared, however, that the resulting compression force was not higher than that produced in expected lifting of a laterally placed mass. This may be caused by a relatively later peak in muscle activity in the unexpected condition, when the net resultant moment is already decreased.

Mechanical stability of the spine must be assured during lifting objects, because loss of stability will impose an injury risk.[26] In the unexpected condition, the moment direction produced is not adequate for the imposed perturbation. In addition, the stiffness of the trunk at the instant of peak resultant net moment appears to be lower compared with the stiffness in the expected condition, as indicated by a lower value of summed muscle forces. Both inadequate direction of the moment produced and the lower stiffness suggest a decreased stability of the spine compared with the expected condition. This stability appears to be too low to sufficiently resist the perturbation caused by the laterally placed mass, as is seen by a deviation in lateral trunk movement of more than 2° compared with the expected condition. Although the resultant trunk movement is small, insufficient muscular stabilization may lead to excessive rotations at the segmental level.[26] Such rotations in combination with a considerable compression force may cause injury to the ligaments or intervertebral disc.[27] Therefore, although the peak loading of the trunk in terms of compression forces does not appear to be increased, the likely decreased stability caused by the unexpected lateral loading may increase the risk of injury.

The quality of the model with which we estimated compression forces is comparable with that of similar models described in literature.[28-30] In these studies, errors of 10 to 20 Nm between estimated muscle moments and net moments in the sagittal plane were described, compared with 11.8 Nm in the current study. The gain described by Granata and Marras[29] was lower than the gain we found (65 *vs.* 82). However, the model we used was not anthropometrically scaled. The anthropometric values used were small, indicating small moments arm of the muscles.[23]

At first sight, our results appear to be in contrast with the results of other experiments on sudden asymmetric loading.[31,32] In these other studies, asymmetric loading was caused by dropping a mass in a box, which was held to the side of the body. Increased activity of the contralateral back muscles and decreased activity of the abdominal muscles were reported. However, comparisons were made with unexpected symmetrical loading and therefore addressed the effect of asymmetry rather than the effect of expectation. In our experiment, we compared expected with unexpected asymmetrical loading to be able to specifically address the effects of expectation. Thomas *et al*[25] and Lavender *et al*[33] studied the effects of expectation in sudden asymmetrical loading. In both experiments, the perturbation was applied by releasing a mass. An increased peak trunk muscle activity in the unexpected condition compared with the values in the expected condition was found. The difference in peak muscle activity with our results may be explained by the nature of the perturbation that is applied. Lower muscle activity was found when the timing of the perturbation was determined by the subjects (as in our experiment) than when the timing was determined by the experimenter (as in the experiments of Thomas *et al*[25] and Lavender *et al*[33]).[34]

Unexpected asymmetrical loading imposes a greater risk of injury than does unexpected symmetric loading. In experiments on symmetrical sudden loading, no increase in low back loading was found.[7,8] In line with the present results, the peak compression force in the lumbar spine was not increased, and the peak net moments were not different between the expected and unexpected condition. Moreover, in symmetrical sudden loading, the effect on kinematics was merely a slowing down of the lifting movement,[7,8] whereas in the present experiment the kinematics of the movement changed, *i.e.*, lateral bending to the opposite side. Therefore, the stability of the trunk appeared to be more disturbed in asymmetrical unexpected loading compared with symmetrical unexpected loading.

In conclusion, unexpected lateral placement of the mass does not increase the peak compression force on the low back. However, total muscle force is decreased and angular excursion is increased, indicating that the stability of the spine is decreased, which may imply an injury risk.

■ Key Points

- Ten subjects lifted a crate in which a mass had unexpectedly been displaced to the left.
- Unexpected lateral mass placement significantly increased the peak resultant net moment of the low back. However, the peak compression force was not increased.
- Trunk lateral bending to the side of the sudden lateral mass and lower muscle forces in the unexpected condition indicated a decreased stability of the spine.

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References

1. Frank JW, Kerr MS, Brooker AS, et al. Disability resulting from occupational low-back-pain: part I. What do we know about primary prevention? A review of the scientific evidence on prevention before disability begins. *Spine* 1996;21:2908–17.
2. Barker ME. A classification of back pain in general practice. *Practitioner* 1987;231:109–12.
3. Andersson GBJ. Epidemiological aspects on low back pain in industry. *Spine* 1981;6:53–9.
4. Burdorf A, Sorock G. Positive and negative evidence of risk factors for back disorders. *Scand J Work Environ Health* 1997;23:243–56.
5. Manning DP, Mitchell RG, Blanchfield LP. Body movements and events contributing to accidental and nonaccidental back injuries. *Spine* 1984;9:734–9.
6. Magora A. Investigation of the relation between low back pain and occupation: part IV. Physical requirements: bending, rotation, reaching and sudden maximal effort. *Scand J Rehab Med* 1973;5:186–90.
7. van der Burg JCE, van Dieën JH. Underestimation of object mass in lifting does not increase the load on the low back. *J Biomech* 2001;34:1447–53.
8. van der Burg JCE, van Dieën JH, Toussaint HM. Lifting an unexpectedly heavy object: the effects on low-back loading and balance loss. *Clin Biomech* 2000;15:469–77.
9. Commissaris DA, Toussaint HM, Hirschfeld H. Anticipatory postural adjustments in a bimanual, whole-body lifting task seem not only aimed at minimising anterior-posterior centre of mass displacements. *Gait Posture* 2001;14:44–55.
10. van Dieën JH, de Looze MP. Directionality of anticipatory activation of trunk muscles in a lifting task depends on load knowledge. *Exp Brain Res* 1999;128:397–404.
11. Oddsson LIE, Persson T, Cresswell AG, et al. Interaction between voluntary and postural motor commands during perturbed lifting. *Spine* 1999;24:545–52.
12. Hof AL. An explicit expression for the moment in multibody systems. *J Biomech* 1992;25:1209–11.
13. Plagenhoef S, Evans FG, Abdelnour T. Anatomical data for analyzing human motion. *Res Q Exercise Sport* 1983;54:169–78.
14. de Looze MP, Bussmann JBJ, Kingma I, et al. Validation of a dynamic linked segment model to calculate joint moments in lifting. *Clin Biomech* 1992;7:161–9.
15. McGill SM. A revised anatomical model of the abdominal musculature for torso flexion efforts. *J Biomech* 1996;29:973–7.
16. Redfern MS, Hughes DB, Chaffin DB. High-pass filtering to remove electrocardiographic interference from torso recordings. *Clin Biomech* 1993;8:44–8.
17. Potvin JR, Norman RW, McGill SM. Mechanically corrected EMG for the continuous estimation of erector spinae muscle loading during repetitive lifting. *Eur J Appl Physiol* 1996;74:119–32.
18. McGill SM. Electromyographic activity of the abdominal and low back musculature during the generation of isometric and dynamic axial trunk torque: implications for lumbar mechanics. *J Orthop Res* 1991;9:91–103.
19. van Dieën JH, Hoozemans MJM, van der Burg JCE, et al. The Importance of Antagonistic Cocontraction of Trunk Muscles for Spinal Loads During Lifting and Pulling Tasks: Implications for Modeling Approaches. IEA 2000/HFES 2000 Congress. San Diego, CA: Human Factors and Ergonomics Society, 2000; pp 617–20.
20. van Dieën JH, Kingma I. Total trunk muscle force and spinal compression are lower in asymmetric moments as compared to pure extension moments. *J Biomech* 1999;32:681–7.
21. van Zandwijk JP. The Dynamics of Force Development: An Experimental and Simulation Study of the Behaviour of Human Skeletal Muscle. Amsterdam: Vrije Universiteit, 1998.
22. Woittiez RD, Huijing PA, Boom HB, et al. A three-dimensional muscle model: a quantified relation between form and function of skeletal muscles. *J Morphol* 1984;182:95–113.
23. van Dieën JH, de Looze MP. Sensitivity of single-equivalent trunk extensor muscle models to anatomical and functional assumptions. *J Biomech* 1999;32:195–8.
24. Chiang J, Potvin JR. The in vivo dynamic response of the human spine to rapid lateral bend perturbation: effects of preload and step input magnitude. *Spine* 2001;26:1457–64.

25. Thomas JS, Lavender SA, Corcos DM, et al. Trunk kinematics and trunk muscle activity during a rapidly applied load. *J Electromyogr Kinesiol* 1998; 8:215–25.
26. Panjabi MM. The stabilizing system of the spine: part I. Function, dysfunction, adaptation, and enhancement. *J Spinal Disord* 1992;5:383–9; discussion, 397.
27. Shirazi-Adl A. Strain in fibers of a lumbar disc: Analysis of the role of lifting in producing disc prolapse. *Spine* 1989;14:96–103.
28. Cholewicki J, McGill SM, Norman RW. Comparison of muscle forces and joint load from an optimization and EMG assisted lumbar spine model: towards development of a hybrid approach. *J Biomech* 1995;28: 321–31.
29. Granata KP, Marras WS. An EMG-assisted model of trunk loading during free-dynamic lifting. *J Biomech* 1995;28:1309–17.
30. Nussbaum MA, Chaffin DB, Baker G. Biomechanical analysis of materials handling manipulators in short distance transfers of moderate mass objects: joint strength, spine forces and muscular antagonism. *Ergonomics* 1999;42: 1597–618.
31. Lavender SA, Shakeel K, Andersson GB, et al. Effects of a lifting belt on spine moments and muscle recruitments after unexpected sudden loading. *Spine* 2000;25:1569–78.
32. Gagnon M, Plamondon A, Gravel D. Effects of symmetry and load absorption of a falling load on 3D trunk muscular moments. *Ergonomics* 1995;38: 1156–71.
33. Lavender SA, Mirka GA, Schoenmarklin RW, et al. The effects of preview and task symmetry on trunk muscle response to sudden loading. *Hum Factors* 1989;31:101–15.
34. Mannion AF, Adams MA, Dolan P. Sudden and unexpected loading generates high forces on the lumbar spine. *Spine* 2000;25:842–52.